Development of a Portable Stand-Alone 20 K Brayton Cycle Helium Refrigeration System

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Abstract. From 2012 to 2015, NASA funded development of the Ground Operations Demonstration Unit for Liquid Hydrogen (GODU-LH2) at Kennedy Space Center that scaled up and matured Integrated Refrigeration and Storage (IRAS) technology. IRAS involves the integration of an external helium refrigeration system with a cryogenic storage tank via an internal heat exchanger and allows advanced operations such as zero boiloff and densification of the liquid. The refrigeration system employed for GODU-LH2 was a Linde LR1620 piston-Brayton cycle machine with an RSX helium compressor. The GODU-LH2 system was installed in two separate shipping containers—one housing the cold-box, compressor, and gas management hardware, and the other the water chiller unit—with 480 VAC and 120 VAC electrical power fed from external hardware at the test site, and data capture and controls achieved using four different, independent software packages. From 2017 to 2019, in support of a densified hydrogen loading test program, the entire system was repackaged into a single, 40' (12 m) shipping container, including the refrigeration system, water chiller, and electrical power distribution hardware, and controls were consolidated into a single Allen Bradley PanelView. Details regarding the design, build-out, and testing of the system will be presented and discussed.

1. Introduction

Development of the Ground Operations Demonstration Unit for Liquid Hydrogen (GODU-LH2) [1] took place at NASA Kennedy Space Center (KSC) in Florida from 2012 to 2015 to scale-up and mature Integrated Refrigeration and Storage (IRAS) [2] technology for large scale liquid hydrogen (LH_2) storage. The high-level GODU-LH2 system consisted of a 125 m^3 horizontal-cylindrical LH_2 tank with a custom-built internal IRAS heat exchanger [3,4], an 880 W at 20 K reverse Brayton cycle helium refrigeration system and associated hardware housed in a standard 12 m ISO shipping container, a custom-built water chiller system housed in a separate 6 m ISO shipping container, and ancillary support systems. Figure 1 shows an overhead view of the GODU-LH2 test site during operation.

GODU-LH2 culminated in a comprehensive test campaign from 2015-2016 wherein advanced capabilities such as zero loss tanker offloads, long duration zero-boil off (ZBO), in-situ liquefaction, and densification of LH_2 were demonstrated [1,5,6]. Subsequently, beginning in 2018, the Nuclear Thermal Propulsion (NTP) program funded [7] a team from NASA Marshall Space Flight Center in Alabama, and KSC to perform a densified hydrogen loading demonstration at the 6 m diameter vacuum chamber

at Test Stand 300 at MSFC using the GODU-LH2 hardware. In support of this effort, the refrigeration system, water chiller, electrical, and controls were packaged into a single 12 m shipping container for ease of transport from KSC to MSFC, constituting a portable, stand-alone 20 K Brayton cycle helium refrigeration system, wherein the only external interfaces were electrical power, liquid nitrogen (LN_2) for refrigeration precooling, pneumatics (shop air or nitrogen) for valve actuation, and vacuum-jacketed (VJ) helium lines connecting the cold box to the IRAS tank.

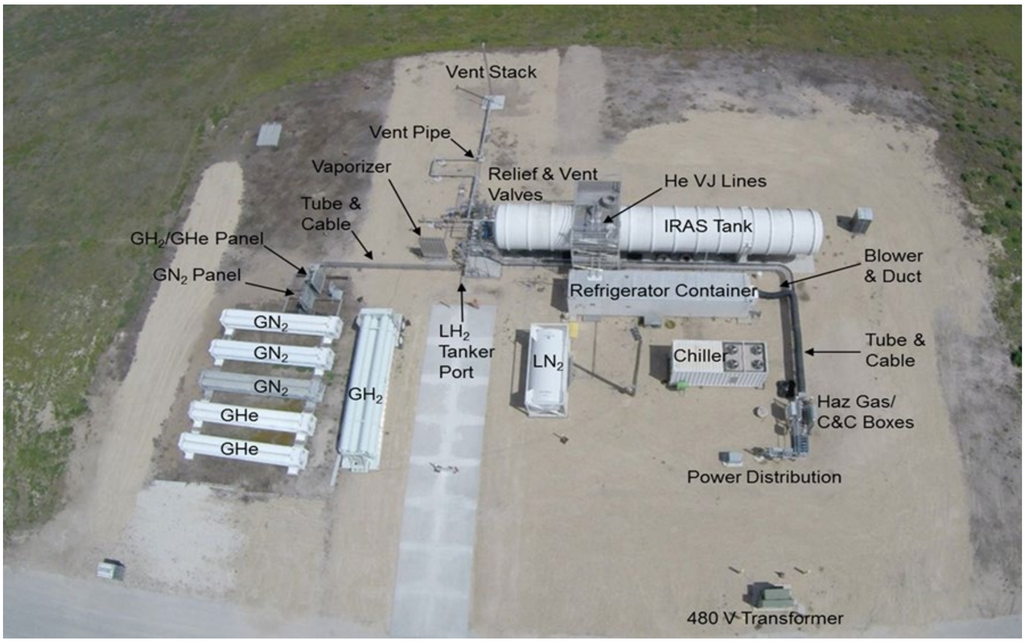

Figure 1. Overhead View of the GOGU-LH2 Test Site in 2015 at NASA KSC

All design, fabrication and check-out testing of the new consolidated refrigeration system took place at KSC between 2018 and 2020, with shipment of the system to MSFC in April of 2021 and densified hydrogen loading tests accomplished in spring of 2022. Details regarding the design, build-out, and testing of the system will be presented and discussed, as well as lessoned learned and future plans.

2. Major Components/Subsystems of the Portable Refrigeration System

The portable refrigeration system is comprised of six primary subsystems: 1. A modified shipping container to house the equipment, 2. The helium refrigerator (cold-box) and compressor, 3. A gas management system to store/supply ultra-high purity (UHP, 99.999%) helium to the compressor, 4. A water chiller unit to supply cooling water to the helium compressor, 5. A high and low voltage electrical system, and 6. A command and control (C&C) system to operate and monitor the equipment.

2.1 Modified Shipping Container

Consolidation of the GODU-LH2 system required a 12 m shipping container with specific modifications to accommodate the equipment and operation of the system. Most notably, the container required a solid partition to split the unit into two compartments, one pressurized and one unpressurized—the latter houses the Freon-to-water heat exchanger and condenser unit for the water chiller system and is open to the atmosphere, and the former contains the bulk of the hardware. The pressurized side is maintained at roughly 374 Pa above atmospheric by a blower unit mounted into the partition wall and was necessary as a risk mitigation during LH_2 operations in case of a leak, as most of electrical hardware could not be rated for flammable environments. Additionally, the blower is fed by a flexible duct with an inlet located 8-m away from any potential hydrogen leak point.

Other modifications to the container include two roll-up garage doors for installation of, and easy access to, the refrigerator cold-box and compressor, and cut-outs to accommodate the VJ helium lines.

2.2 Helium Refrigerator & Compressor

The heart and soul of the refrigeration system are a Linde LR1620 refrigerator and an RSX helium compressor, which are installed in the pressurized side of the shipping container just inside the two garage doors. The LR1620 is a reverse-Brayton cycle unit that employs two parallel piston expanders with 4-stages of recuperation, while the RSX compressor supplies helium to the cold-box at roughly 16.5 bar gauge pressure, at flow rates up to 22 g/s. LN_2 precooling can be utilized to more than double the cooling capacity of the system if desired. Rated capacities of the LR1620/RSX are 850 W and 390 W at 20 K with and without LN_2 precooling respectively; however, the actual GODU-LH2 unit slight outperformed the rated values during initial acceptance testing in 2015, with capacities of 883 W and 446 W at 20 W with and without LN_2 precooling respectively. Figure 2 shows the refrigerator cold-box and compressor installed in the modified shipping container.

Control of the refrigeration power is accomplished via a 1000 W heater internal to the refrigerator, on the cold helium supply, immediately downstream of the expanders. This heater responds to a user-defined temperature setpoint established in the C&C system.

Figure 2. Linde LR1620 Cold-Box (foreground) and RSM Helium Compressor (background) installed in the Modified Shipping Container

2.3 Gas Management System

The gas management system acts as a buffer to maintain an adequate quantity of helium in the system during cooldown and warmup. Two helium accumulators are employed, with volumes of 276 L and 454 L, and are pressurized to roughly 13.8 bar from UHP helium gas bottles prior to using the refrigeration system. Helium is supplied to the cold box from the accumulators, and controlled automatically via on/off solenoid valves inside the unit in response to the operational pressure.

2.4 Chilled Water System

The chilled water system was originally custom-built for the GODU-LH2 project to operate in flammable environments, and sized to remove 96 kW, supplying up to 95 L/min at a temperature range of 20°C and 24°C. Most of the original hardware was reused when consolidating into a single shipping

container, including pumps, Freon-to-water heat exchanger, condenser unit, control valves, and instrumentation, but the system was completely reconfigured to fit the new space constraints. The most significant hardware change was a smaller 246 L water reservoir versus the original 1,136 L tank. A mix of 33% ethylene glycol and 66% distilled water is supplied directly to the RSM helium compressor via PVC plumbing, and routes back to the reservoir in a closed loop. The chiller is controlled through the C&C system via a custom program built using the original software and parameters as a guide.

2.5 Electrical and Command & Control Systems

Electrical requirements of the hardware spanned numerous voltages and power levels, but it was desired to have a single interface point to the site power source, therefore it was necessary to build-in all the required hardware to the modified shipping container. A panelboard brings in 480VAC, 600A, 3-phase power from the site/facility, and then the power is distributed to the cold-box, a RSX helium compressor, and a power relay box that services the water chiller. A 15 KVA minipower center is also employed to step-down the 480 VAC to 120 VAC to power the remaining hardware, and C&C system.

The original GODU-LH2 controls consisted of three independent Windows computers interfacing with the building automation control (BAC) system which was reading and controlling the field sensors and actuators, building automation temperature controls, the chilled water supply system, the Linde LR1620/RSX, and IRAS tank instrumentation. This was reduced to one tightly integrated Allen Bradley Panelview human machine interface, with the capability to communicate on the Honeywell building automation control system protocol, interface with the Linde equipment and to communicate directly with the Allen Bradley process automation controller (PLC). This replicated the original system control and monitoring screens while adding a capability to control additional field installed valve actuators, IRAS tank monitoring sensors, along with Ethernet based remote operation capability.

Figure 3. Command & Control Box with Panelview (left), Power Relay Box (middle), and Chilled Water System Hardware (right)

3. System Layout

Figures 4 and 5 present the overall interior layout of the portable refrigeration system with major components noted, and a view of the container during transport from KSC to MSFC in 2021. The unpressurized compartment is in the foreground of figure 5, with the cut-outs and grating for airflow in/out of the condenser unit clearly visible, and the round port (covered with yellow tape) is where the flexible duct for the blower unit interfaces.

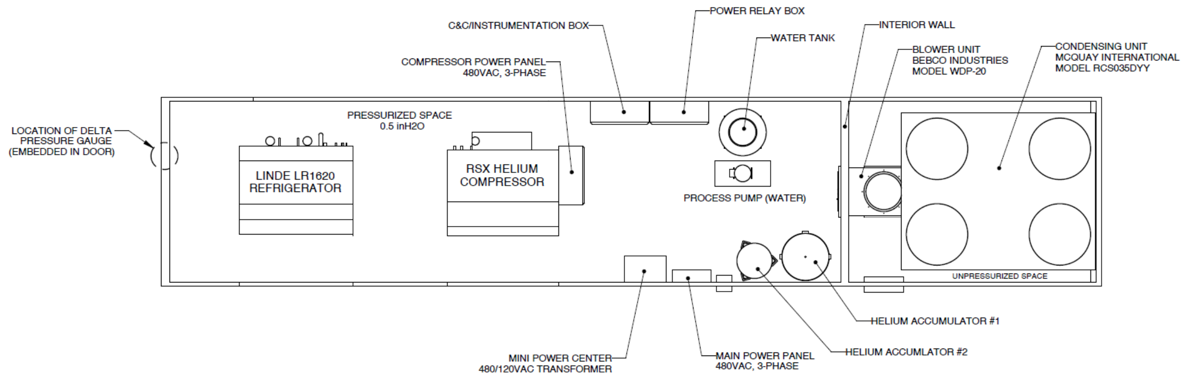

Figure 4. Overall Interior Layout of the Portable Refrigeration System

Figure 5. Portable Refrigeration System During Transport from KSC to MSFC

4. External Interfaces & Site Requirements

Table 1 summarizes the external interfaces to the portable refrigeration system, as well as the associated site requirements. Additional site provisions could be necessary as well to aid in operating or maintaining the system depending on the application. These include small LN_2 storage and transfer hardware for executing helium clean-up cycles using a charcoal adsorber, small vacuum pumps for servicing interconnect piping, and hand tools. Use of the flexible duct for the blower is only necessary for applications where the system is utilized within a classified hazardous/flammable zone [8].

Table 1. External Interfaces & Site Requirements for the Portable Refrigeration System

Description	Type	Location	Interface	Site Requirement
VJ Helium Lines	Fluid	Penetrating rear container wall and interfacing vertically to the cold-box	2x bayonets (Linde P/N: 8055-1-136), 4-bolt flanges, 304L SS both sides	N/A
Liquid Nitrogen Feed Line	Fluid	Rear container wall	1/2-in 37° flare, male	25 L/hr
Actuation Pressure	Fluid	Rear container wall	1/4-in 37° flare, male	5.5 bar, air or nitrogen
Helium Charging	Fluid	Rear container wall	1/4-in 37° flare, male	UHP helium
Helium Relief Vent	Fluid	Rear container wall	1-in 37° flare, male	Local clear area around vent
Cold Nitrogen Vapor Vent	Fluid	Rear container wall	1-in 37° flare, male	Local clear area around vent
Water Drain/Fill	Fluid	Rear container wall	3/4-in hose fitting, male	246-L, 65/35 distilled water-to-glycol
Electrical Power	Electrical	Front contianer wall	3x ROXTECH RGM63 entry seals	480 VAC, 3-phase, 600 amp, 2x 500 MCM per phase
Aera Network	C&C	Rear container wall	Modular, Ethernet	N/A

5. Commissioning & Testing

Initial commissioning of the portable refrigeration system took place at KSC in October 2020, with the system reaching capacities >400 W at 20 K without LN_2 precooling. Due to a scheduling conflict at Test Stand 300 at MSFC the transport of the unit was delayed until April 2021. In the interim, the system was prepared for the trip, which included securing and isolating various pieces of hardware, draining the chilled water reservoir, and staging supporting test equipment inside the shipping container.

5.1 Densified Hydrogen Testing at NASA-MSFC

With the 125 m^3 IRAS tank from GODU-LH2 having been transported and installed at the test stand at MSFC in 2019, the arrival of the portable refrigeration system led to a speedy integration of the entire system. By the Winter of 2022, the entire system was ready to begin densified hydrogen testing. Figure 6 shows the total system installed at Test Stand 300.

Figure 6. Portable Refrigeration System with the GODU-LH2 IRAS Tank at Test Stand 300 at NASA-MSFC

Following numerous setbacks, including failure of the variable frequency drive on the LR1620 cold-box, Freon leaks in the chilled water system, moisture contamination issues in the VJ helium lines, and an inadequate LN_2 feed system, testing finally commenced in March of 2022. Roughly 37,850 L of LH_2 was loaded into the IRAS tank, and the refrigeration system operated at full capacity to densify the hydrogen while the tank was maintained at a positive pressure using helium.

Due to a variety of factors, the target LH_2 densification temperature of 15 K was not achieved during the test; instead, the loading demonstration was carried out with 17 K liquid. Densified LH_2 was successfully fed from the IRAS tank into a 3,785 L test vessel located inside the 6 m test stand vacuum chamber on two separate occasions, leading to most of the testing goals being achieved. A more detailed report of the densified loading demonstration will be published at a later date.

6. Lessons Learned & Future Improvements

Testing at MSFC led to many lessons learned and desired future improvements to the portable refrigeration system. Of particular note was the discovery that the chilled water system had difficulty operating continuously at ambient temperatures <4°C. As the unit was originally designed to operate at KSC in central Florida, where such temperatures are rare, provisions were not put in place to accommodate the low ranges seen in northern Alabama in the winter and early spring. And due to the chiller control scheme shutting down Freon compressors to protect them from damage, over time the chilled water temperature rose until the helium compressor also automatically shut down. Ultimately a work-around was found using different combinations of chiller components in manual mode to keep the chiller operating most of the time, but the ambient temperature was always the deciding factor, and the persistent issue led to costly delays. As such, if the system is to be further utilized in colder regions, it will be necessary to revisit the chilled water system design and controls to ensure a consistent, uninterrupted water supply to the helium compressor.

An additional major shortcoming of the portable refrigeration system is the inability of the current Panelview and software to record data. Although it is possible to remotely control the system and read data in real-time via an ethernet connection, a capability to record data is not currently available. Therefore, a necessary future improvement will be to update the command & control system to accommodate data acquisition, as this is crucial for not only understanding the performance of the refrigeration system, but performing troubleshooting activities.

7. Future Work

At the time of this report, the portable refrigeration system still resides at Test Stand 300 at MSFC, and remains configured with the GODU-LH2 IRAS tank. There are plans to utilize the system once again to perform densified hydrogen at the test stand in 2023. Further out, the Exploration Ground Systems (EGS) program at KSC is exploring the possibility of employing the portable refrigeration system to help manage boiloff losses on the 4,700 m^3 LH_2 storage tank [9] which was recently completed at launch pad 39B at KSC. Not only is this new tank the largest LH_2 storage tank in the world, but it also possesses IRAS capability via an internal heat exchanger. Filling of the tank is planned for late summer 2023, and the refrigeration system would be employed soon thereafter if the program chooses to implement it.

8. Conclusion

Development of a portable, stand-alone, Brayton cycle helium refrigeration system capable of 880 W at 20 K was presented and discussed. Designed and constructed at NASA Kennedy Space Center (KSC), the portable refrigeration system utilized hardware that originally supported the Ground Operations Demonstration Unit for Liquid Hydrogen (GODU-LH2) project at KSC from 2012-2016, including the Linde LR1620 helium refrigerator with RSM compressor, and a custom-built chilled water system. The GODU-LH2 hardware was consolidated into a single 12 m shipping container, with the only required external interfaces being vacuum-jacketed helium lines connecting the refrigerator to the load, 480VAC power, liquid nitrogen for helium precooling, and shop air or nitrogen for valve actuation pressure.

The portable refrigeration system was completed in late 2020 at KSC and transported to NASA Marshall Space Flight Center (MSFC) in Alabama in April 2021 to be reunited with the 125 m^3 GODU-LH2 Integrated Refrigeration and Storage (IRAS) liquid hydrogen (LH_2) tank at Test Stand 300. The combined system was then used to perform densified hydrogen loading tests in 2022 and is currently awaiting further testing at MSFC in 2023. Additionally, the system may be utilized at the new 4,700 m^3 LH_2 sphere at launch pad 39B at KSC to manage boiloff losses following the initial LH2 fill in late summer 2023, via an internal IRAS heat exchanger that was built into the tank.

9. References

[1] Notardonato W U, Swanger A M, Fesmire J E, Jumper K M, Johnson W L and Tomsik T M 2017 Final test results for the ground operations demonstration unit for liquid hydrogen, *Cryogenics* **88,** Pages 147-155

[2] Swanger A M, Notardonato W U, Johnson W L and Tomsik T M 2016 Integrated Refrigeration and Storage for Advanced Liquid Hydrogen Operations, *Cryocooler 19*: Proceedings of the 2016 International Cryocooler Conference, San Diego, California, Pages 513-522

[3] Swanger A M, Notardonato W U and Jumper K M 2015 ASME Section VIII Recertification of a 33,000 Gallon Vacuum-Jacketed LH2 Storage Vessel for Densified Hydrogen Testing at NASA Kennedy Space Center, Proceeding of the ASME Pressure Vessels and Piping Conference, Massachusetts, Boston, PVP2015-45625

[4] Swanger A M, Jumper K M, Fesmire J E and Notardonato W U 2015 Modification of a Liquid Hydrogen Tank for Integrated Refrigeration and Storage*, IOP Conf. Ser.: Mater. Sci. Eng.* **101** 012080

[5] Swanger A M, Notardonato W U, Fesmire J E, Jumper K M, Johnson W L and Tomsik T M 2017 Large scale production of densified hydrogen to the triple point and below*, IOP Conf. Ser.: Mater. Sci. Eng*. **278** 012013

[6] Notardonato W U, Swanger A M, Fesmire J E, Jumper K M, Johnson W L and Tomsik T M 2017 Zero boil-off methods for large scale liquid hydrogen tank using integrated refrigeration and storage, *IOP Conf. Ser.: Mater. Sci. Eng.* **278** 012012

[7] Houts, M G., et al., NASA's Nuclear Thermal Propulsion Project, AIAA SPACE 2015 Conference and Exposition, Pasadena, California, AIAA 2015-4523

[8] NFPA 497 Recommended Practice for the Classification of Flammable Liquids, Gases, or Vapors and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas, 2021, (Quincy, MA: National Fire Protection Association)

[9] Fesmire J E and Swanger A M 2021 Overview of the New LH_2 Sphere at NASA Kennedy Space Center, Virtual Presentation, DOE/NASA Advances in Liquid Hydrogen Storage Workshop, https://www.energy.gov/eere/fuelcells/advances-liquid-hydrogen-storage-workshop

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